

Available at [www.sciencedirect.com](http://www.sciencedirect.com)<http://www.elsevier.com/locate/biombioe>

# Particle emissions from pellets stoves and modern and old-type wood stoves

Linda S. Båfver<sup>a,\*</sup>, Bo Leckner<sup>b</sup>, Claes Tullin<sup>a</sup>, Morten Berntsen<sup>c</sup>

<sup>a</sup> SP Technical Research Institute of Sweden, Department of Energy Technology, Box 857, 501 15 Borås, Sweden

<sup>b</sup> Chalmers University of Technology, Department of Energy Technology, 412 96 Göteborg, Sweden

<sup>c</sup> Teknologisk institutt, Pb 2608 St Hanshaugen, NO-0131 Oslo, Norway

## ARTICLE INFO

### Article history:

Received 27 June 2008

Received in revised form

8 May 2011

Accepted 13 May 2011

### Keywords:

Wood

Pellets

Domestic combustion

Emissions

## ABSTRACT

The purpose of this work is to characterise particle emissions from pellets stoves and modern and old-type residential wood stoves. The mass concentration of particulate material in the hot flue gas was 19–82 mg/MJ, roughly the same for wood stoves and pellets stoves, but the old-type wood stoves tended to emit even higher quantities. Furthermore, during combustion of wood logs the considerably higher emission of organic gaseous carbon indicates an additional contribution to the emission from secondarily formed condensable organic particles.

The particle mass emitted was dominated by fine particles ( $<1\ \mu\text{m}$ ) in all cases. The fine particle maximum was displaced towards larger size during inefficient combustion, e.g. during the start-up phase. The number concentration of particles from wood stoves was  $1.0 \cdot 10^{14}$ – $6.0 \cdot 10^{14}$  #/MJ, from pellets  $3.0 \cdot 10^{13}$ – $5.0 \cdot 10^{13}$  #/MJ, and in all cases dominated by fine particles. Efficient combustion of pellets resulted mainly in inorganic particles, dominated by potassium sulphate and potassium chloride. Zinc, the second most frequent metal, and calcium showed the highest concentrations among the less volatile components. The lowest concentration detected was for cadmium, about  $10^5$  times lower than for potassium.

© 2011 Elsevier Ltd. All rights reserved.

## 1. Introduction

Residential heating may cause locally high concentration of particulate matter in the ambient air. This could be harmful, especially in densely populated areas. A well-known example is the 1952 London smog, which caused several deaths. Today, residential heating still is an important local source of ambient air particles. Just to take two examples of quite different origin: emission from tiled coal stoves in Krakow, Poland [1] and from residential wood boilers in Lycksele, Sweden [2]. However, not all residential combustion of biomass causes high emissions. Large differences in emissions between modern and old-type residential wood boilers

have been shown [3]. Residential boilers heat up water that is circulated through a piping system to heat an entire house, in contrast to stoves from which heat radiates directly into the room. Stoves and boilers are two alternative residential biomass combustion devices. Their particle emissions need to be treated separately because of differences in design and use, e.g. the boilers can be connected to a heat storage tank and the size of the fire-box is considerably larger in boilers than in stoves. These differences lead to a very broad range in emission performance.

The open fireplace is the forerunner to the wood stove and is still used in many homes world-wide, mostly for cosy and aesthetical combustion. In a comprehensive study Muhlbalder

\* Corresponding author. Tel.: +46 10 5165501; fax: +46 33 131979.

E-mail address: [linda.bafver@sp.se](mailto:linda.bafver@sp.se) (L.S. Båfver).

0961-9534/\$ – see front matter © 2011 Elsevier Ltd. All rights reserved.

doi:10.1016/j.biombioe.2011.05.027

Dasch [4] found that particle emissions from open fireplaces were between 100 and 1100 mg/MJ. In recent studies on wood stoves, mass concentration of particles has been reported in the range of 86–780 mg/MJ [5–8]. Consequently, the particle concentrations in the flue gas from wood stoves varied about a factor of ten in the measured cases, and even higher concentrations can occur. Pellet stoves provide a modern alternative to wood stoves. They are designed to only burn pelletized wood, from which particle concentrations in the flue gas in the range of 13–81 mg/MJ have been reported [9,10], consequently lower than in the flue gas from wood stoves.

To avoid high particle emissions from residential biomass combustion, there is a need for more knowledge about the particle emissions, and especially about differences between modern and old-type techniques. The present study aims at characterising the particle emission from pellets stoves and modern and old-type wood stoves. The particle emission will be characterised with respect to mass concentration, number concentration, size distribution, chemical content of particles, and transient effects.

## 2. Methods

The experimental work contains two parts. In Table 1 an overview of all measurement cases is given. Firstly, the particle emissions from six modern wood stoves, one wood-cooking stove and three pellet stoves were measured with respect to PM<sub>10</sub> and PM<sub>2.5</sub>. Secondly, particle emissions from two old-type wood stoves, one modern wood stove, and two pellet stoves were investigated in more detail: mass concentrations, number concentrations, mass and number particle-size distributions. Chemical composition of the emitted particles was also studied for one of the pellet stoves. One of the modern wood stoves and one of the pellet stoves were included in the first as well as in the second experimental part

**Table 1 – Overview of measurement cases. W. L. = wood logs, W. P. = wood pellets.**

Case	Stove	Fuel
<b>PART I</b>		
MoWo1	Modern wood stove 1	W.L.
MoWo2	Modern wood stove 2	W.L.
MoWo3	Modern wood stove 3	W.L.
MoWo4	Modern wood stove 4	W.L.
MoWo5	Modern wood stove 5	W.L.
MoWo6	Modern wood stove 6	W.L.
WoCook	Wood cooking stove	W.L.
Pe1	Pellets stove 1	W.P. 1
Pe2	Pellets stove 2	W.P. 1
Pe3-wp2	Pellets stove 3	W.P. 2
<b>PART II</b>		
O-T Wo1-wood	Old-type wood stove 1	W.L.
O-T Wo2-wood	Old-type wood stove 2	W.L.
MoWo1(II)	Modern wood stove 1	W.L.
Pe1(II)	Pellets stove 1	W.P. 1
Pe1(II)-wp3	Pellets stove 1	W.P. 3
Pe4_a	Pellets stove 4	W.P. 1
Pe4_b	Pellets stove 4	W.P. 1

of the work. The emissions are presented in mg pollutant (or number of particles) per MJ of fuel supplied, calculated from measured concentrations and fuel analyses. Transient effects and emissions during the different phases of combustion were investigated.

### 2.1. Stoves

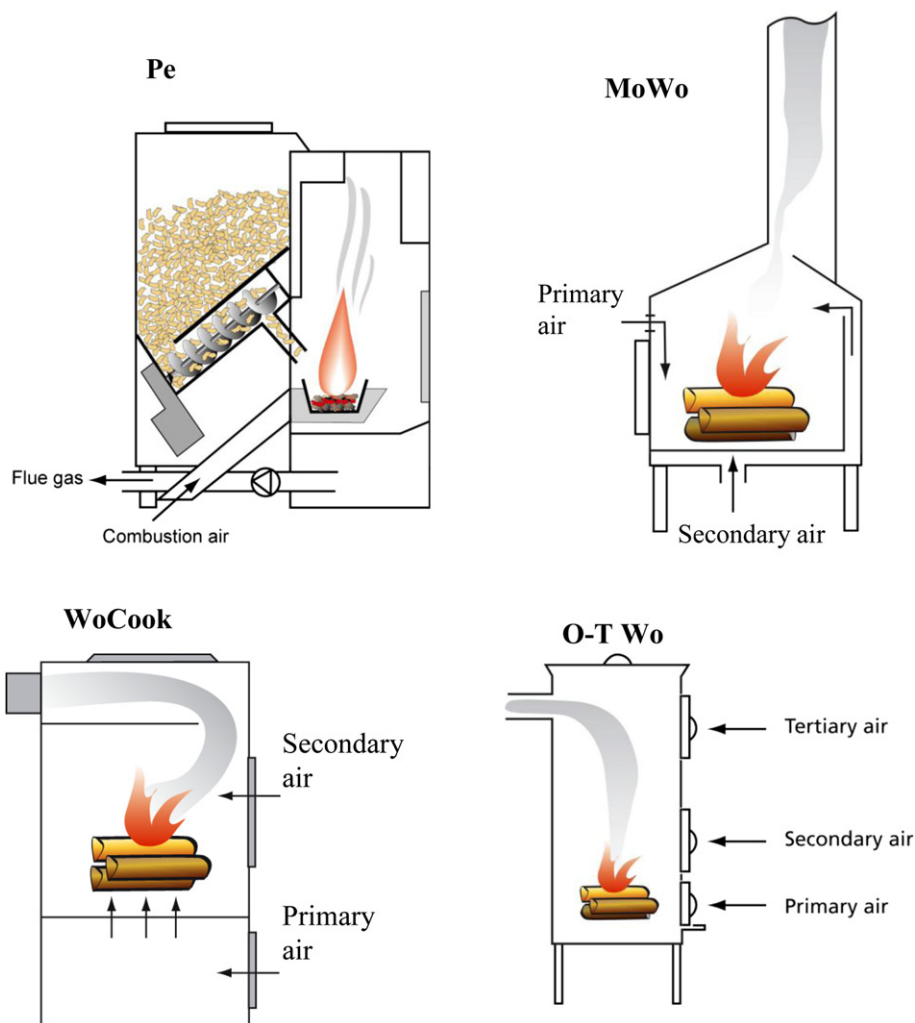
Fig. 1 shows a pellet stove (Pe), a modern wood stove (MoWo), a modern wood cooking stove (WoCook and an old-type wood/coal stove (O-T Wo)). The pellet stoves are usually equipped with internal pellet storage. The pellets are transported upwards from the bottom of the storage by a screw. Then the pellets continuously fall into a burner cup where combustion takes place. The flame is directed upwards and can be seen from the outside of the stove, since the front of the pellet stove usually has a glass window. The flue gases are drawn out of the stove by a flue gas fan. This design is used in three of the stoves investigated, but the fourth stove has a primary air fan instead. In the modern wood stove, the air supply is more sophisticated compared with old-type techniques. The primary air is supplied close to the door, consequently protecting the glass door from soot, and the secondary air is heated before reaching the fire-box. The cooking stove and old-type stove resemble more the principles of an open fireplace. The pellets stoves, the modern wood stoves and the modern cooking stove in the study are available on the market today. However, the old-type stoves have been chosen with respect to their “age” and are from the 1960’s (The old stoves are made of cast iron and work well.)

### 2.2. Fuels

The fuels are described in Table 2. The chemical composition of the wood logs and wood pellets was similar, except for the moisture content that was approximately half in the pellets as in the wood logs. The ash content of the biomass was 0.3–0.5%. A difference in chemical composition can be noted in the pellet qualities: the third pellets type had four times as high nitrogen content and at least twice as high sulphur content as the first and second type of pellets. This difference in composition is due to some waste wood from production of parquet floor, containing urea-based glue, which is mixed into the third kind of pellets. The first and second types of pellets were made of stem wood without additives. The wood pellets had a diameter of 6 or 8 mm and a length of 5–20 mm. Each batch of wood logs consisted of three logs of approximately same mass. The mass of each wood log was 0.6 kg. The corresponding length was 0.3 m.

### 2.3. Measurement techniques

Particle emissions from the heating devices were sampled from hot flue gas in the chimney (about 200 °C for the wood stoves, and lower for the pellets stoves). PM<sub>10</sub> and PM<sub>2.5</sub> were measured according to the EPA Metod 201 A [11] for measurements of particulate matter in the stack. Flue gas is drawn through a heated (180 °C) probe and a heated cyclone (cut-off 10 µm at PM<sub>10</sub>-measurement and 2.5 µm at PM<sub>2.5</sub>-measurement) to a heated filter for sampling of PM<sub>10</sub> and



**Fig. 1 – Schematic figures of a pellet stove (Pe), a modern wood stove (MoWo), a modern wood cooking stove (WoCook), and an old-type wood/coal stove (O-T Wo).**

PM<sub>2.5</sub>. After the filter, flue gas is condensed and dried prior to registration of flue gas volume in a dry gas metre. Total mass concentrations were evaluated by sampling and weighing of dust collected on filters according to Swedish Standard [12]. The principles for measurement of total particle mass are the same as for PM<sub>10</sub> and PM<sub>2.5</sub>, except that the cyclone is excluded. Mass size distributions were determined by a DLPI (Low-Pressure Impactor, manufactured by Dekati Ltd), ranging between aerodynamic particle diameters of 30 nm to 10 µm. The DLPI and the probe connected to it were heated (110 °C). Number concentrations and number size distributions were determined using an ELPI with filter stage (Electrical Low-Pressure Impactor, Dekati Ltd), which ranges from aerodynamic diameter 7 nm to 8 µm. Greased (Apiezon L solved in carbon tetrachloride) aluminium foils were applied on the impactor stages in DLPI and ELPI during measurements of mass and number size distributions (no chemical analyses were made during these measurements). Prior to measurement, the greased foils were heated to 120 °C and kept for 2 h to evaporate the solvent. For sampling to ELPI, the temperature of the flue gas needed to be lowered (below 40 °C). To

preserve the particle size distribution present in the hot flue gas conditions, the gas was diluted with particle-free and dry air in two steps using ejector dilutors (7·7 = 49 in dilution ratio). The first dilution took place under heated conditions (180 °C) to avoid condensation and particle growth.

In one of the pellet cases the content of unburned carbon was investigated by analysing the particles obtained from sampling of the mass concentration of particles for total carbon and carbonate carbon, according to EN13137 [13]. Unburned carbon, i.e. the sum of organic carbon and elemental carbon, is calculated by subtracting the carbonate carbon from the total carbon. It has been shown earlier (for example Reference [14]) that particle emissions from a pellet stove are dominated by fine particles (<1 µm). In the present work further analyses on the fine particle fractions were carried out in some additional measurements. In those cases, particles were sampled on non-greased Al-foils in the DLPI and the fine size fractions were analysed with SEM-EDX (Scanning Electron Microscopy - Electron Dispersive X-ray). Grease was excluded to not disturb the EDX-analysis. For quantitative analysis of inorganic components, DLPI-

**Table 2 – Elemental analyses and heating values of the fuels. The moisture is in mass percent related to wet fuel and the other data are in mass percent related to dry fuel. W.L. = wood logs and W.P. = wood pellets.**

	W.L.	W.P. 1, 6 mm	W.P. 2, 8 mm	W. P. 3, 6 mm
Moisture	15	7.6	7.6	6.5
Lower heating value (MJ/kg)	19.0	19.1	19.0	18.9
Carbon %	50.6	49.9	50.2	49.7
Oxygen %	42.7	43.4	43.2	43.7
Hydrogen %	6.4	6.2	5.9	6.1
Nitrogen %	0.05	0.05	0.08	0.20
Sulphur %	<0.01	<0.01	<0.01	0.02
Ash %	0.3	0.4	0.5	0.3
Ash analysis (g/kg dry ash)				
Calcium, Ca	–	223	–	–
Potassium, K	–	87.9	–	–
Silicon, Si	–	37.7	–	–
Magnesium, Mg	–	34	–	–
Manganese, Mn	–	30.1	–	–
Iron, Fe	–	18.1	–	–
Phosphorus, P	–	14.8	–	–
Aluminium, Al	–	8.7	–	–
Sodium, Na	–	5.9	–	–
Barium, Ba	–	3.6	–	–
Titanium, Ti	–	0.6	–	–
Ash analysis (mg/kg dry ash)				
Zinc, Zn	–	3150	–	–
Copper, Cu	–	250	–	–
Lead, Pb	–	120	–	–
Chromium, Cr	–	55	–	–
Nickel, Ni	–	45	–	–
Molybdenum, Mo	–	27	–	–
Cadmium, Cd	–	26	–	–
Arsenic, As	–	<20	–	–
Vanadium, V	–	11	–	–
Cobalt, Co	–	10	–	–

sampling was performed using greased polycarbonate-foils followed by wet-chemical analysis by ICP-MS (Inductively Coupled Plasma Mass-Spectrometry) and IC (Ion-Chromatography) on each size fraction separately. A method to analyse the mass and molar fractions of alkali compounds, based on TOF-SIMS (Time-of-flight Secondary Ion Mass Spectrometry), developed by Sjövall [15], was used on fine size fractions from separate DLPI-samples on non-greased polycarbonate-foils. The flue gas content was also characterised with respect to carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), oxygen (O<sub>2</sub>) and total organic carbon (TOC), in all cases to give information about the combustion conditions. TOC was measured as methane-equivalents and calculated to concentration of carbon atoms, i.e. organic gaseous carbon (OGC), prior to presentation. In most cases, the NO<sub>x</sub>-emission was recorded as well. The measurement principles of the gas analysers are non-dispersive infrared (CO, CO<sub>2</sub>), paramagnetism (O<sub>2</sub>), flame ionisation (TOC/OGC), and chemiluminescence (NO<sub>x</sub>). The NO<sub>x</sub> emissions are presented as NO<sub>2</sub>-equivalents.

#### 2.4. Operating procedures and measurement strategy

In all cases the draught in the chimney was adjusted to natural draught, showing a negative pressure of about 15 Pa. The combustion in the wood stoves and the cooking stove was initiated with a minor ignition fire consisting of sticks of wood. The time for supplying a new batch of logs was defined

from the point when CO<sub>2</sub>-concentration reached less than 4%, and no visible flames were observed. Then, a batch of wood was supplied on the glow bed of the previous fire. During ignition of the batch the air valve was fully open. Thereafter it was adjusted to a burning time of 50 ± 5 min burning time for each batch, i.e. the time for a burning cycle. All emission data are valid for full burning cycles, except for those focussing on a specific combustion phase. Part 1 of the study considers emission data after the ignition cycle, while the ignition cycle is included in Part 2. The variation in particle emission between different combustion phases is studied. In Fig. 2 these phases are illustrated by measured concentrations of CO<sub>2</sub>, CO and TOC during combustion of one batch of wood logs in the old-type wood stove. The first phase is start-up (5 min in this study), typically showing high concentrations of CO and TOC while the volatile matter is leaving the biomass. Thereafter the intermediate phase starts and is in force until the concentration of CO<sub>2</sub> drops and the burnout phase steps in. The end of the burnout phase is defined by the end of a wood batch (CO<sub>2</sub> < 4%, and no visible flames were observed).

The pellets stoves were operated continuously at partial load. The monitored outputs were in the range of 3–5 kW. During Part 1 of the study, the measurements of emissions presented in this study are from stable conditions, i.e. the pellets stoves were operated a while before measurements. During Part 2 of the study, measurements started from

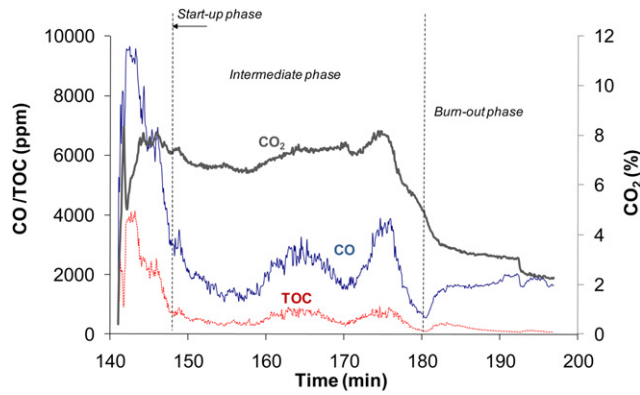


Fig. 2 – The combustion phases during combustion of a batch of wood logs (from the first old-type wood stove).

ignition of pellets, i.e. the pellets stoves were at room temperature when the measurements started.

### 3. Results and discussion

The emission data are summarised in Table 3. The CO and OGC emissions reveal a large difference in combustion conditions between wood stoves and pellet stoves. CO ranged between 1200 and 3200 mg/MJ for the wood stoves and between 92 and 270 mg/MJ for the pellet stoves. The highest CO value was recorded for one of the cases with the old-type wood stove (O-T Wo1-wood). For the wood stoves, OGC ranged between 110 and 300 mg/MJ and for the pellets stoves it was 2–11 mg/MJ. Obviously, the pellets stoves represent the most efficient combustion cases.

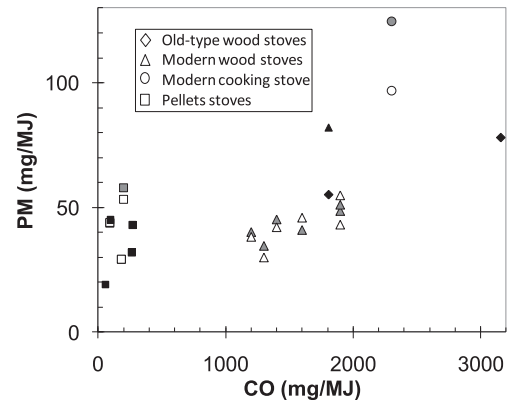


Fig. 3 – Emissions of particulate matter (PM) plotted against carbon monoxide (CO). Black symbols indicate  $PM_{tot}$ , grey symbols  $PM_{10}$  and open symbols  $PM_{2.5}$ .

The concentration of emitted  $NO_x$  was 70–110 mg/MJ from wood-fired stoves, showing no clear relation to overall air-ratio. As the fuel source was constant, the variation can be related to the local air-ratios in respective combustion case, owing to the stove design or natural variations during the combustion of wood logs.  $NO_x$  from the more controlled combustion of wood pellets seems to increase with increasing nitrogen content in the fuel, indicating a dominance of  $NO_x$  formed from fuel-nitrogen.

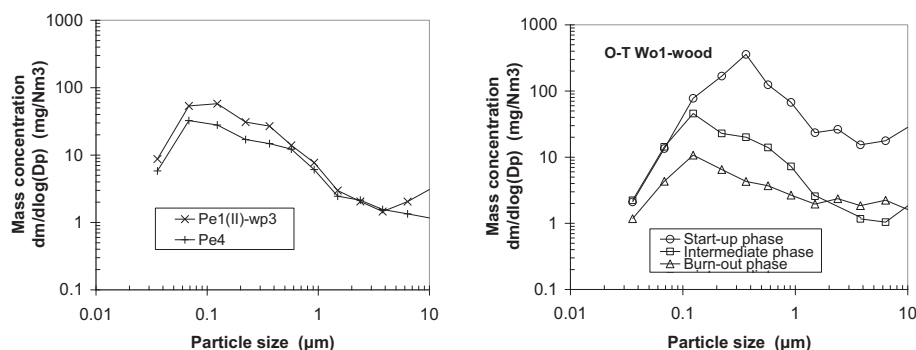
#### 3.1. Mass concentration of particles

In the plot of mass concentration of particles against CO in Fig. 3 two groups of biomass-fired stoves are distinguished: pellets stoves and modern wood stoves. Furthermore, the two

Table 3 – Measurement cases and emissions of  $CO_2$  (carbon dioxide), CO (carbon monoxide), OGC (organic gaseous carbon),  $NO_x$  (nitrogen oxides), and mass and number concentrations of particles during combustion. The measurement data are presented as mg pollutant per megajoule fuel supplied where nothing else is noted.  $NO_x$  is presented as  $NO_2$ . Excess air factor = Real air quantity/Theoretical air quantity.

Case*	$CO_2$ (%)	CO	OGC	$NO_x$	$PM_{10}$	$PM_{2.5}$	$PM_{tot}$	PM (#/MJ)	Excess air factor
PART I									
MoWo1	5.2	1600	150	110	41	46	—	—	3.9
MoWo2	8.8	1900	210	82	49	43	—	—	2.3
MoWo3	6.7	1400	200	74	45	42	—	—	3.0
MoWo4	5.2	1200	140	81	40	38	—	—	3.9
MoWo5	6.2	1900	170	77	51	55	—	—	3.3
MoWo6	8.7	1300	220	85	34	30	—	—	2.3
WoCook	4.2	2300	300	96	124	97	—	—	4.9
Pe1	3.1	92	4	68	44	44	—	—	6.6
Pe2	5.6	200	7	71	58	53	—	—	3.7
Pe3-wp2	8.0	180	2	83	29	29	—	—	2.5
PART II									
O-T Wo1-wood	5.5	3200	440	70	—	—	78	6.0E+14	3.7
O-T Wo2-wood	4.8	1800	110	84	—	—	55	1.0E+14	4.3
MoWo1(II)	6.4	1800	200	—	—	—	82	6.0E+14	3.2
Pe1(II)	2.9	96	8	68	—	—	45	3.0E+13	6.8
Pe1(II)-wp3	3.3	270	11	170	—	—	43	5.0E+13	6.2
Pe4_a	7.4	260	5	—	—	—	32	3.7E+13	7.5
Pe4_b	4.5	57	—	—	—	—	19	—	4.3



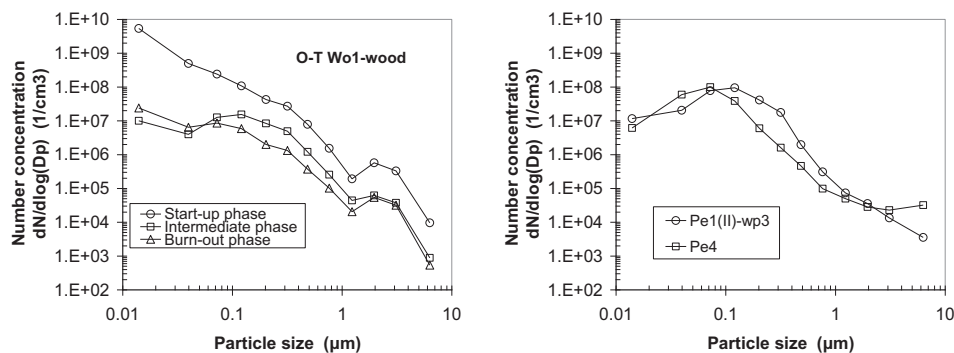


**Fig. 4 – Mass size distributions of particles measured at the different combustion cases of the old-type stove during wood firing (O-T Wo-wood), and as mean values during combustion periods of two pellet cases (Pe1(II)-wp3 and Pe4\_a). The concentrations are normalised to 13% O<sub>2</sub>.**

cases with old-type wood stoves showed different results, one of them overlapping with the group modern stoves, and the other one showing higher particle emission as well as higher CO. The pellets stoves and modern wood stoves emitted about the same particle concentrations, except for a wood case with higher particle emission. The two groups were distinguished by different CO-concentrations; the wood stoves emitted more CO. Finally, the cooking stove showed considerably higher emissions, both of particles and CO. Assuming  $PM_{tot}$  to be equal to  $PM_{10}$ , the emission of particles was 19–58 mg/MJ for pellets, 34–82 mg/MJ for modern wood stoves, and 55–78 mg/MJ for old-type wood-fired stoves. A possible explanation of the case with high particle emission from a modern wood stove is that the ignition fire was included in the measurement (Part 2), which was not the case for remaining wood stoves (Part 1). The wood-cooking stove does not fit into any of the groups: it had the highest particle emission among the devices investigated, 124 mg/MJ. Furthermore, the high concentration of gaseous OGC (Table 3) indicates that secondary formation of organic particulate material can be expected outside the chimney.

The emissions from one of the wood stoves and one of the pellet stoves were investigated with respect to both  $PM_{10}$ ,  $PM_{2.5}$  and  $PM_{tot}$ , i.e. the modern stove 1 was used in case MoWo1 as well as MoWo1(II), and the pellet stove 1 is used in case Pe1 as well as Pe1(II). In one of these comparisons Pe1/Pe1(II)

$PM_{tot} \approx PM_{10} \approx PM_{2.5}$  and in one comparison (MoWo1/MoWo1(II))  $PM_{tot} > PM_{10} \approx PM_{2.5}$ . In case MoWo1(II) the ignition fire was included, in contrast to MoWo1. This indicates enhanced emissions of particles larger than 10 μm during the ignition fire and small or negligible emissions of coarse particles in other cases. Only in one case, the cooking stove (WoCook), representing the highest particle emission in this study, there was significantly higher emission of  $PM_{10}$  than of  $PM_{2.5}$ , 124 and 97 mg/MJ respectively. In all cases together, the particle mass emitted was dominated by fine particles, illustrated in Fig. 4 by a few mass size distributions. During a whole combustion cycle, the mass-fraction of  $PM_1$  and  $PM_{2.5}$  was 81–94% and 84–96%. The emissions vary from one combustion phase to another. During combustion of wood logs, higher concentrations were observed for all particle sizes during start-up with a fine-particle maximum of around 0.4 μm, while the maxima for the intermediate and burnout phases peaked around 0.1 μm. The intermediate phase was characterised by a higher concentration of fine particles than the burnout phase, but the two phases showed roughly the same concentration of coarse particles. The mass size distributions during combustion of pellets had maxima around 0.1 μm and clearly showed that fine particles dominated the emission. This is similar to the intermediate phase during combustion of wood logs, and a consequence of different combustion phases overlapping each other as pellets are continuously fed into the burner cup.



**Fig. 5 – Number size distributions of particles measured at the different combustion cases of the old-type stove during wood firing (O-T Wo-wood), and as mean values during combustion periods of two pellet cases (Pe1(II)-wp3 and Pe4\_a). The concentrations are normalised to 13% O<sub>2</sub>.**

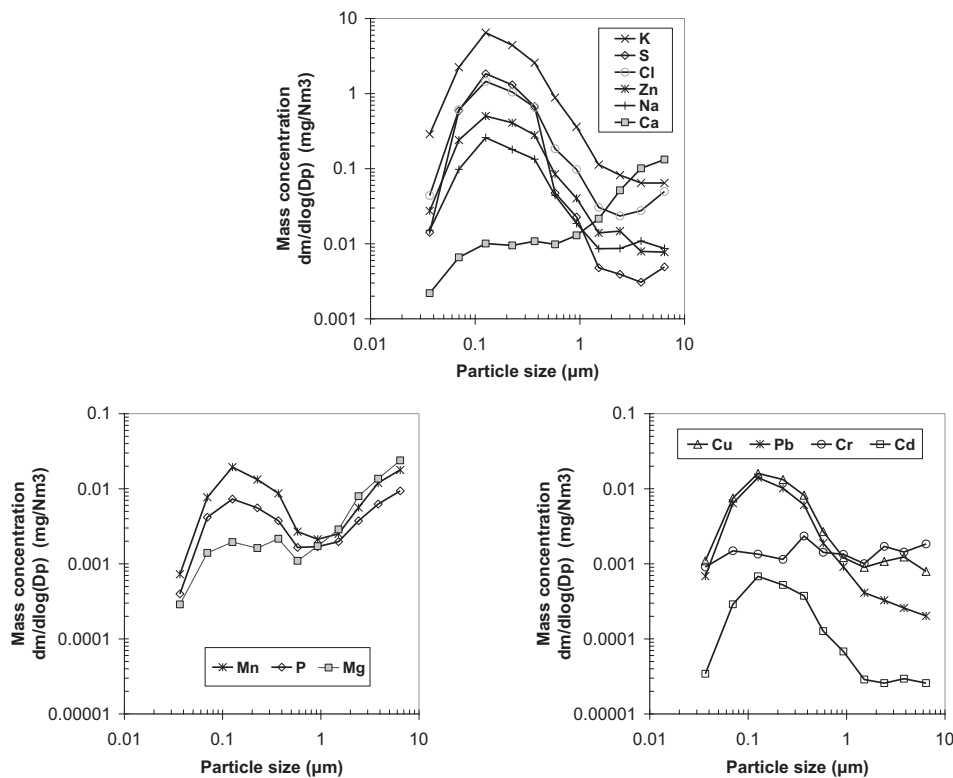


Fig. 6 – Mass size distributions of sulphur, chlorine, phosphorous and metals from the pellet stove.

### 3.2. Number concentration and size distribution

The number concentration of particles from wood stoves was  $1.0 \cdot 10^{14}$ – $6.0 \cdot 10^{14}$  #/MJ, and the number emitted from combustion of pellets was smaller, in the range of  $3.0 \cdot 10^{13}$ – $5.0 \cdot 10^{13}$  #/MJ. Fig. 5 shows that the number of particles emitted was dominated by fine ones. The number of ultrafine particles ( $PM_{0.1}$ ) is very high, especially at start-up. High emission of ultrafine particles has also been demonstrated by others [16,17]. It is an important parameter, possibly affecting the air quality more than particle mass [18]. The start-up phase is characterised by a higher particle emission than normal stable operation, whereas the final phase of fuel conversion, consisting mostly of combustion of char, has the lowest number of particles similar to the particle mass shown in Fig. 4.

### 3.3. Particle composition

The particles emitted from one of the pellet cases, representing efficient combustion and low mass concentration of particles (Pe4\_b), was investigated with respect to chemical content. The particles consist to 17 wt% of unburned carbon, i.e. the sum of elemental carbon and organic carbon. The EDX, ICP-MS, and IC analyses of the particles showed that the main inorganic components of the fine particles were potassium, sulphur, chlorine and oxygen. According to the TOF-SIMS analysis potassium sulphate was more abundant than potassium chloride, and the concentration of potassium carbonate is low in relation to potassium sulphate and chloride. Fig. 6 presents mass size distributions of the investigated

inorganic components from the pellet combustion. Potassium, sulphur, chlorine, zinc and sodium, in the order of the most abundant, showed fine peaks, following the total mass size distribution presented in Fig. 4. Calcium, which is less volatile than the preceding components, had the next highest concentration with a size peak in the coarse size range. Finding less volatile elements in the form of coarse particles indicates that they originate from withdrawal from the fuel bed, which is different from the fine particles, which are formed from the vapour phase. Among the lower concentrations, manganese and phosphorous showed maxima in the fine particle range, and manganese also has a coarse maximum. Furthermore, magnesium showed a single maximum in the coarse range. The trace elements copper and lead had fine maxima at the same concentration level as manganese, while the concentration of chromium was similar but without a distinct peak. Cadmium was present in the lowest concentration, represented by a clear fine maximum in its size distribution.

## 4. Conclusions

This study presents emission data for modern and old-type residential stoves fired with wood logs and wood pellets. Based on the quantitative information presented, the following conclusions can be drawn:

- Particles were characterised in the hot flue gas. Modern pellets stoves showed low mass concentrations of particles, as well as low CO-concentrations. The modern wood stoves

emitted about the same particle concentrations as the pellet stoves in a majority of the cases, but more CO. The old-type wood stoves tended to emit even higher quantities of particles and CO.

- The mass concentration of particulate material in the chimney was roughly the same for wood stoves and pellets stoves. However, the considerably higher (typically more than 30 times) emission of organic gaseous carbon from combustion of wood logs indicates an additional contribution to the emission from secondarily formed condensable organic particles.
- In all cases the particle mass emitted was dominated by fine particles ( $<1\ \mu\text{m}$ ), and there was a small or negligible fraction of coarse particles. During the start-up of wood combustion, higher concentrations of all particle sizes were observed, and the fine particle maximum in the mass size distribution was around  $0.4\ \mu\text{m}$ , while the maxima of the intermediate and burnout phases peaked around  $0.1\ \mu\text{m}$ . The concentration of fine particles was higher during the intermediate phase than during the burnout phase, but the two phases showed roughly the same concentration of coarse particles. Finally, enhanced mass of particles larger than  $10\ \mu\text{m}$  was indicated during the ignition fire.
- The number of particles emitted was dominated by the ones smaller than  $1\ \mu\text{m}$ . The number concentration of particles from wood stoves was somewhat higher than from combustion of pellets. The start-up phase was characterised by a higher particle emission than during the intermediate phase. Furthermore, the burnout phase, representing combustion of char, showed the lowest number of particles.
- Efficient combustion of pellets resulted mainly in inorganic particles with potassium sulphate as a major compound, peaking in the fine size range in the same way as the total mass size distribution. Also potassium chloride was present in a high concentration. Zinc, showing a fine maximum, was the second most frequent metal after potassium. Calcium had the highest concentration among the less volatile components, resulting in a coarse maximum. The concentrations of manganese and phosphorous were lower and contained fine as well as coarse maxima. Copper and lead had approximately the same concentration level as the former components, and their clear fine-particle maxima indicate that they were formed by condensation of inorganic vapour. Finally, the concentration of cadmium was about  $10^5$  lower than the concentration of the main component potassium, but having a fine maximum.
- A modern wood cooking stove was included in the study. It was noted for higher emissions than the other stoves. Only under the unfavourable combustion conditions in the wood cooking stove (WoCook) there was a significant concentration of particles in the upper coarse range, between  $\text{PM}_{10}$  and  $\text{PM}_{2.5}$ .

## Acknowledgements

The financial support from the Swedish Energy Agency, the EU CRAFT project CLEANAIR, and StatoilHydro ASA is gratefully acknowledged.

## REFERENCES

- [1] Jaszczur T, Lewandowski M, Szweczyk W, Zaczekowski A, Butcher T. Coal-fired tile stoves – efficiency and emissions. *ASHRAE Trans* 1995;101:573–84.
- [2] Omstedt G, Johansson C, Gidhagen L. 2004. Air quality dispersion modelling of wood smoke emissions in residential areas in Sweden, In: Proceedings of 9th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes. Garmisch-Partenkirchen, Germany.
- [3] Johansson LS, Leckner B, Gustavsson L, Cooper D, Tullin C, Potter A. Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets. *Atmos Environ* 2004;38:4183–95.
- [4] Muhlbaler Dasch J. Particulate and gaseous emissions from wood-burning fireplaces. *Environ Sci Technol* 1982;16: 639–45.
- [5] McDonald JD, Zielinska B, Fujita EM, Sagebiel JC, Chow JC, Watson JG. Fine particle and gaseous emission rates from residential wood combustion. *Environ Sci Technol* 2000;34: 2080–91.
- [6] Purvis CR, McCrillis RC, Kariher PH. Fine particulate matter (PM) and organic speciation of fireplace emissions. *Environ Sci Technol* 2000;34:1653–8.
- [7] Hedberg E, Kristensson A, Ohlson M, Johansson C, Johansson P-Å, Swietlicki E, et al. Chemical and physical characterization of emissions from birch wood combustion in a wood stove. *Atmos Environ* 2002;36:4823–37.
- [8] Gullett BK, Touati A, Hays MD. PCDD/F, Pcb, HxCbz, PAH, and PM emission factors for fireplace and woodstove combustion in the San Francisco Bay Region. *Environ Sci Technol* 2003;37: 1758–65.
- [9] Johansson LS. Characterisation of particle emissions from small-scale biomass combustion. Thesis for the degree of licentiate of engineering, Department of Energy Technology, Chalmers University of Technology, Göteborg, Sweden; 2002.
- [10] Boman C. Particulate matter and products of incomplete combustion from residential biomass pellet appliances – emissions and potential for future technology. Licentiate thesis, Faculty of Energy Technology and Thermal Process Chemistry, Umeå University, Umeå, Sweden; 2003.
- [11] EPA Method 201 A – Determination of  $\text{PM}_{10}$  emissions (Constant sampling procedure).
- [12] SS-EN 13284-1. Stationary source emissions – determination of low range mass concentration of dust, Part 1: manual gravimetric method; December 2001.
- [13] EN13137. Characterization of waste – determination of total organic carbon (TOC) in waste, sludges and sediments; 2001.
- [14] Johansson LS, Leckner B, Tullin C, Sjövall P. Particle emissions from biomass combustion in small combustors. *Biomass Bioenergy* 2003;25:435–46.
- [15] Sjövall P, Lausmaa J, Tullin C, Högberg J. Kemisk/fysikalisk karaktärisering av avlagringar. Report 750. Stockholm: Värmeforsk; 2001 [In Swedish].
- [16] Kinsey JS, Kariher PH, Dong Y. Evaluation of methods for the physical characterization of the fine particle emissions from two residential wood combustion appliances. *Atmos Environ* 2009;43:4959–67.
- [17] Lamberg H, Nuutinen K, Tissari J, Ruusonen J, Yli-Pirilä P, Sippula O, et al. Physicochemical characterization of fine particles from small-scale wood combustion. *Atmospheric Environment, Corrected Proof*, in press.
- [18] Lighty JS, Veranth JM, Sarofim AF. Combustion aerosols: factors governing their size and composition and implications to human health. *J Air Waste Manag Assoc* 2000; 50:1565–618.